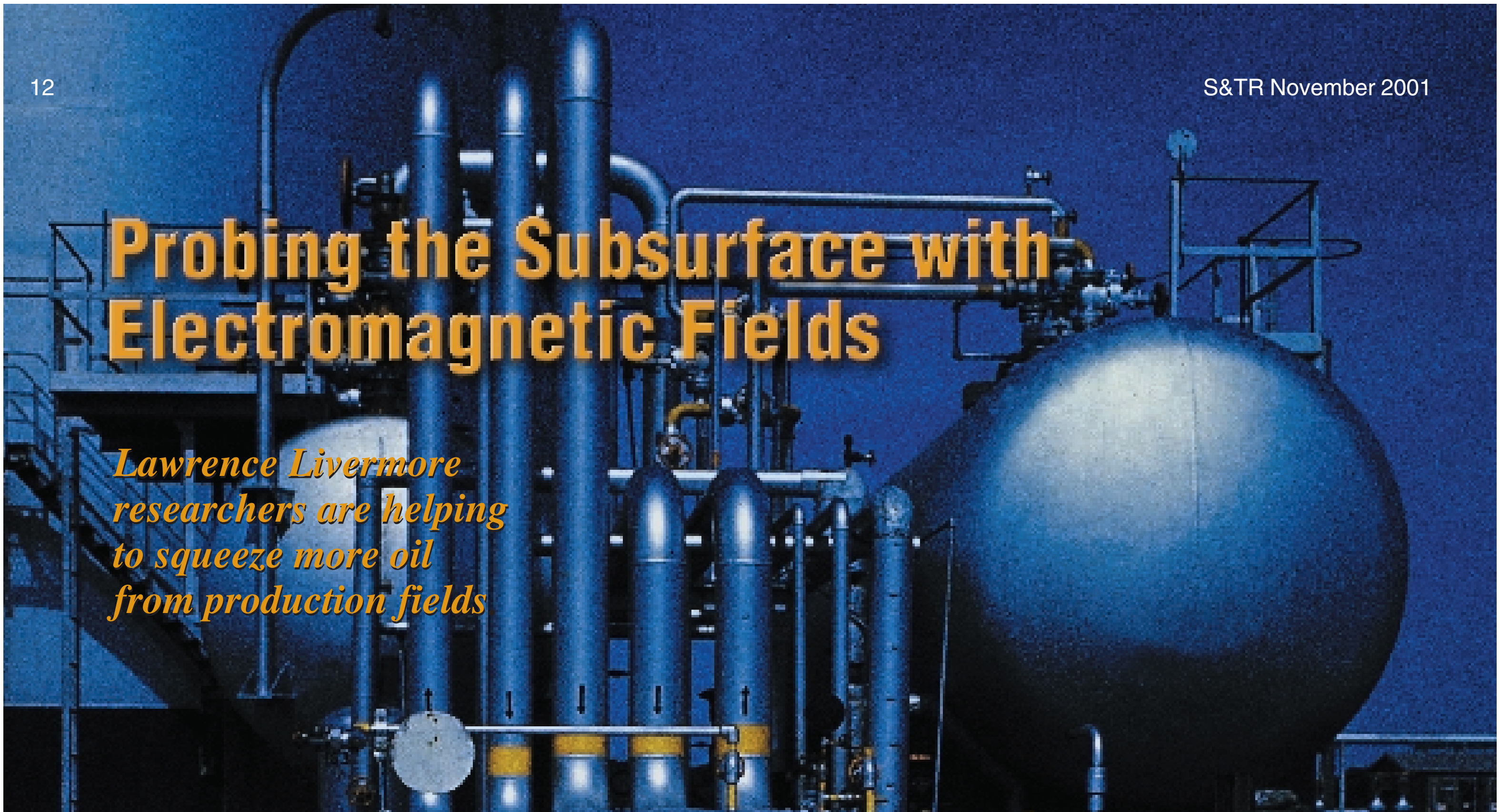


Probing the Subsurface with Electromagnetic Fields

Lawrence Livermore researchers are helping to squeeze more oil from production fields

FOR years, energy experts have been warning the U.S. about our increasing dependence on imported oil. Although this country has abundant oil reserves, oil companies usually recover only about 32 percent of the oil in a typical reservoir. That is, for every barrel of oil withdrawn from an oil field, two are left behind. Recovering all the oil discovered is impossible; however, increasing production levels is a constant goal. Extracting even a relatively small additional amount of oil is important to the nation's energy future.

Researchers at Department of Energy national laboratories such as Lawrence Livermore have been working with U.S. oil companies to improve enhanced oil recovery (EOR) technologies so that more oil can be extracted from domestic production fields. One standard EOR technique, called waterflooding, pumps water underground to wash out oil trapped in rocks. Another method sends steam down wells to heat the oil and drive it toward production wells. A promising EOR method is injecting carbon dioxide underground. With carbon dioxide flooding, as much as 25 percent additional oil could be extracted that is not presently retrievable with traditional EOR methods.

With all of these methods, it is important to monitor the EOR operation underground so that field personnel can track the injected material over time to better position production wells for increased recovery. Also, because EOR operations can last for several years, oil companies can save money when high-resolution imaging reveals a problem early, such as a layer of rock that is preventing water or gas from flowing through a field.

A technique to view underground fluids and gases, called crosswell electromagnetic (EM) imaging, is a valuable tool for monitoring steamflooding and waterflooding. Because of its demonstrated success with these two standard EOR methods, crosswell EM imaging is being tested by Lawrence Livermore researchers as a potential method to track carbon dioxide injected underground for EOR. The research team's early success with mapping carbon dioxide injected into a central California oil field has prompted discussion of using the technology to monitor the underground sequestration (long-term storage) of carbon dioxide from industrial operations to help the environment. Finally, the team has also demonstrated the technology's usefulness in geothermal well drilling and as a method to monitor toxic waste spills.

Exploiting Resistivity Differences

Crosswell EM imaging takes advantage of the differences in how electromagnetic fields are induced within various materials. (See the box on p. 14.) Rocks containing a lot of water, for example, usually conduct electricity better than rocks containing oil, typically in the form of droplets bound to tiny rock pores. EM imaging is complementary to traditional seismic imaging, which uses sound waves to visualize underground geologic strata. Seismic imaging, however, has limited capability to distinguish between oil and other fluids. "Seismic methods are best for mapping structure, while electromagnetic methods are sensitive to the types of fluids within rocks," says Lawrence Livermore physicist and lead researcher Barry Kirkendall.

Over the past several years, Livermore researchers have been improving the capability of crosswell EM imaging to map underground waterfloods. Field experiments have demonstrated the technology at the University of California's Richmond Field Station in the San Francisco Bay Area and the Lost Hills oil field operated by Chevron USA in central California.

The successful imaging from the Lost Hills project prompted a new study to determine the usefulness of the technique for monitoring carbon dioxide flooding at a nearby site also operated by Chevron. The new study, begun last year, is funded by Laboratory Directed Research and Development in partnership with Chevron USA. The study combines both field work and laboratory experiments.

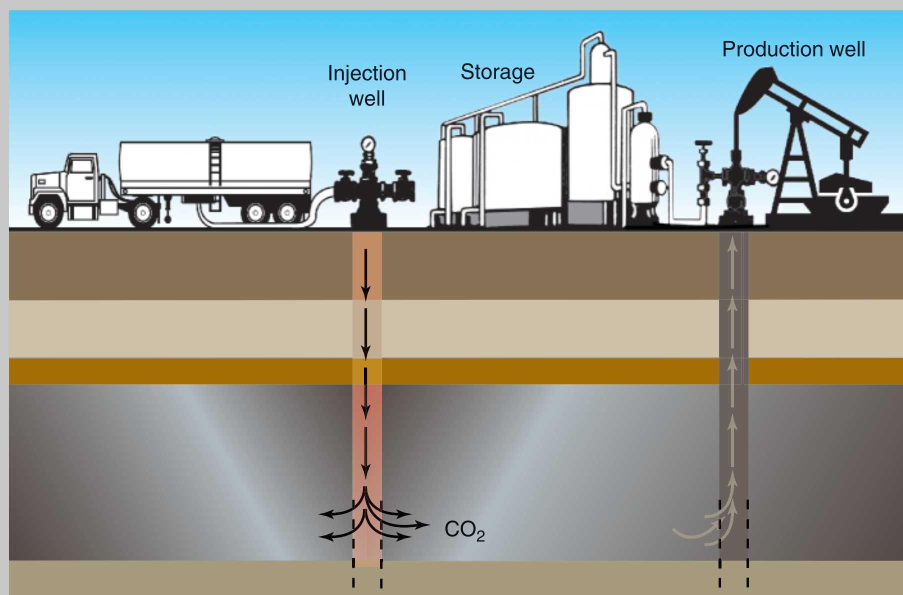
Kirkendall says that interest in using carbon dioxide as an EOR technique is increasing because its oil recovery rate can be higher than that of waterflooding or steamflooding. Pumping carbon gas or liquid carbon dioxide deep into the ground is done with a set of injection wells. The carbon dioxide remains in liquid form if it is injected deeper than about 550 meters. Above that level, the lower pressure turns the liquid into a gas. Liquid carbon dioxide has a bit more miscibility to drive oil from rocks than does gaseous carbon dioxide, but both phases are useful to oil recovery efforts.

Underground, carbon dioxide travels slowly through rock layers, mixing with oil droplets in rock pores, lowering the droplets' viscosity, and thereby easing their extraction by production wells. When the now thinner oil reaches the surface, about 10 percent of the carbon dioxide comes out with the oil; the remaining 90 percent remains below ground. A good deal of water is also extracted with the oil and is separated and pumped back into the earth.

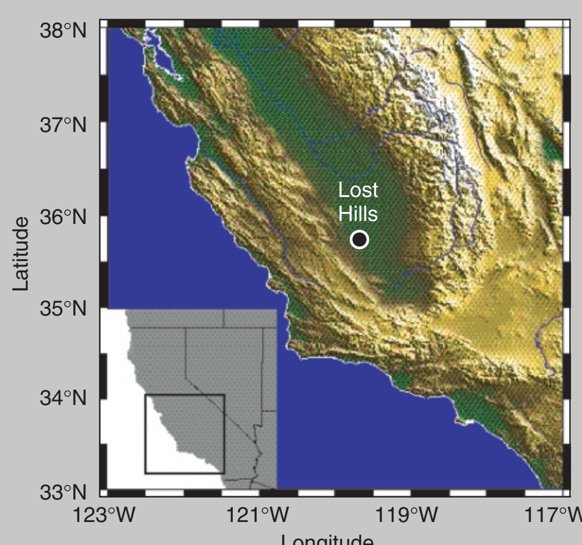
Test at Lost Hills

The current Lost Hills project tests the ability of crosswell EM imaging to map the location of carbon dioxide and remaining from a previous, multiyear waterflood. The study uses Lawrence Livermore field equipment from the first Lost Hills for characterizing a waterflood. The equipment includes two new field vehicles that were obtained from DOE's Nevada Test Site. One vehicle is outfitted for signal transmission and the other for signal reception and data processing.

Kirkendall says that the Lost Hills project is especially valuable because the team obtained images of the underground environment in August 2000, some four months before Chevron began to inject carbon dioxide. These baseline images were acquired for comparison while tracking carbon dioxide, oil, and water



To enhance oil recovery, carbon dioxide (CO_2) is pumped underground, where it mixes with oil, lowering the oil's viscosity and thereby improving the extraction by production wells. About 10 percent of the carbon dioxide comes out with the extracted oil. A good deal of water from previous waterflooding is also extracted with the oil.



The tests for crosswell electromagnetic imaging have been conducted mostly at the Lost Hills oil field in central California. The field is operated by Chevron USA.

over time. In April 2001, the researchers acquired subsurface data for comparison to the baseline, preinjection images. In October 2001, a six-month snapshot was taken. Additional data will be acquired in March 2002.

To acquire data, the team uses two fiberglass-cased observation wells located some 30 meters apart. One of four carbon dioxide injectors is located directly between the observation wells. A receiver is sent down one well and a transmitter is placed down the second. Each tool is connected by wire to its respective field vehicle. The vehicles, in turn, are connected by fiber-optic cable. Data are acquired at three frequencies—2, 4, and 10 kilohertz—over the 92-meter depth interval between 455 and 550 meters, the depth at which carbon dioxide was injected.

Following extensive computer processing, the data recorded in April yielded images in the two-dimensional plane between the transmitter and receiver wells. The images show that carbon dioxide is slowly moving through the field, mixing with oil droplets, and pushing them to production wells. However, the images also show that carbon dioxide is trapped in certain places instead of getting dispersed throughout the area. “The tests suggest that crosswell EM has the ability to characterize carbon dioxide displacement from water and oil in underground rock strata,” says Kirkendall.

Laboratory Work Aids Effort

The team is working to better discriminate carbon dioxide from oil, a major task because both have similar

Crosswell EM Imaging on the Job

Crosswell electromagnetic (EM) induction imaging technology was developed by researchers at Lawrence Livermore and Lawrence Berkeley national laboratories and scientists at Schlumberger, a supplier of oil production services (see *S&TR*, August 1996, pp. 20–23). The technology is designed to provide high-resolution images of underground deposits of oil, water, gas, and other materials. It was originally developed to provide oil companies with a means to monitor oil recovery techniques such as waterflooding. The technology is currently being tested for carbon dioxide flooding, a form of enhanced oil recovery, and for monitoring toxic spills.

Crosswell EM imaging is a complementary technique to traditional seismic imaging, which involves sending sound waves through underground geologic formations and investigating the different speeds at which the waves travel. Instead of measuring sound-wave velocities, the method measures electrical resistivity—or conversely, conductivity—of different materials to electromagnetic fields and waves. For example, rock formations containing water conduct current much more readily, that is, have a lower resistance, than rocks containing oil and gas. Injecting a field with steam or water—two common methods for forcing more oil out of rocks—lowers the resistivity of the rock. Images taken before, during, and after injection are compared to determine the progress of this enhanced recovery process.

Measuring electrical resistivity near a well is a longstanding technique in oil exploration and mapping geologic strata. Such measurements are usually made out to about a meter around the well. Crosswell EM induction permits mapping subsurface resistivity at multiple frequencies between wells to yield a detailed, two-dimensional picture.

The system consists of a transmitter tool deployed in one well and a receiver tool deployed in a second well, typically 30 meters away. The tools are connected to specially designed field vehicles obtained last year from the Department of Energy’s Nevada Test Site. The transmitter uses a vertical axis coil wrapped with 100 to 300 turns of wire tuned to broadcast a single frequency that induces currents to flow in underground surrounding rocks. The induced current, in turn, generates a second magnetic field. At the receiver well, a custom-designed sensor detects the total magnetic field, consisting of the magnetic field from the induced currents as well as the primary magnetic field generated by the transmitter. A commercial lock-in amplifier, located in the receiver vehicle, extracts signals that are coherent with the transmitted signal while rejecting all noise.

In practice, the receiver is held steady at a fixed depth while the transmitter is lowered over the entire vertical length of the underground zone of interest. Then the receiver is held steady at a fixed depth, and the receiver is moved up and down. By positioning both the transmitter and receiver tools at various depths within the zone of interest, researchers create an image of the resistivity distribution for the geologic strata between the wells.

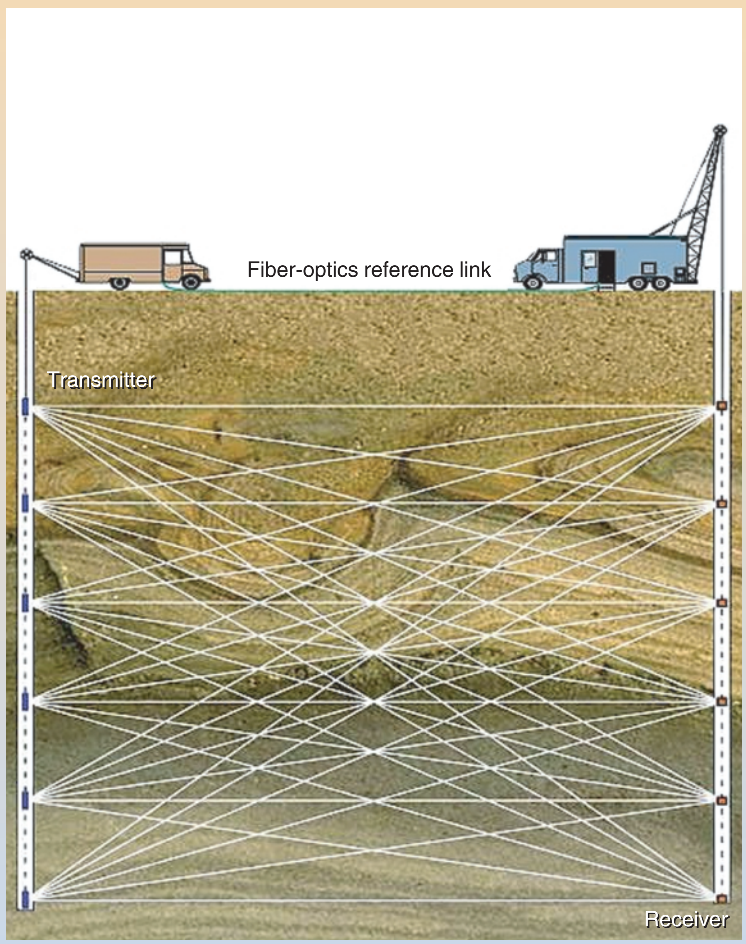
The entire process is done at two and, increasingly, three different frequencies (2 kilohertz, 4 kilohertz, and 10 kilohertz), because each frequency yields additional information. Lower frequencies give greater penetration through the subterranean rock layers, while higher frequencies give greater resolution. The transmitting frequencies are chosen based on the distance between the transmitting and receiving wells, resistivity measurements of the field taken by Chevron USA, and the unique characteristics of the rock layers based on laboratory work on the core samples.

An inversion algorithm developed at Sandia National Laboratories processes the collected data, essentially voluminous measurements of magnetic fields. The method is called inversion processing because magnetic field data of varying amplitude and phase are changed to electrical conductivity data corresponding to depth and distance between the transmitter and receiver wells. It takes several weeks to

At the Lost Hills oil field, the receiver truck has lowered the underground sensor deep into the receiver well to detect the electromagnetic currents given off by the transmitter tool. The truck contains equipment for signal reception and data processing. Lawrence Livermore technicians Duane Smith (left) and Pat Lewis stand by the truck.

completely process all the data and build several possible underground computer models. Choosing the best model is aided by the results from laboratory tests on core samples from the field and from subsurface data obtained by the oil company working that field.

An outgrowth of the separate receiver and transmitter configuration is a single tool containing a transmitter located on top of several receivers arrayed vertically. This technique was used last year in a venture between Lawrence Livermore researchers, Schlumberger, and the California Energy Commission at several sites in California and Nevada. The technique looks in 360 degrees around an observation well and can take measurements some 10 meters into the formation.



Crosswell electromagnetic induction uses a transmitter tool deployed in one well and a receiver tool deployed in a second well. The tools are connected to specially designed field vehicles. The transmitter broadcasts a frequency that induces currents to flow in underground surrounding rocks. The induced current, in turn, generates a second magnetic field. At the receiver well, a sensor detects the magnetic fields. The receiver is held steady at a fixed depth while the transmitter is lowered over the entire vertical length of the underground zone of interest. Then the receiver is held steady at a fixed depth and the receiver is moved up and down. In this way, researchers create an image of the resistivity of the geologic strata located between the transmitter and receiver.

electrical signatures. In addition, Kirkendall relies on experimental data supplied by Livermore geophysicist Jeff Roberts. Working in his laboratory, Roberts measures the electrical properties of core samples taken from deep underground by Chevron engineers. The experiments determine the electrical properties of the production field's rocks as they are saturated with fluids and carbon dioxide.

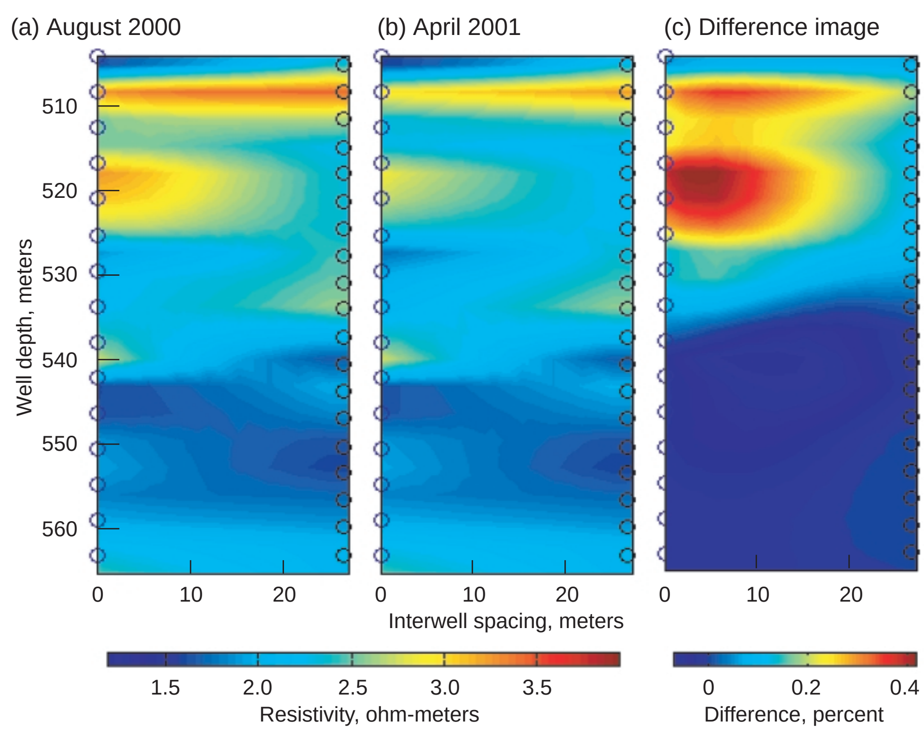
Roberts had conducted similar experiments on core samples from the Lost Hills waterflood study, but he had to modify some procedures and techniques so that he could use carbon dioxide as an injectate. The current experimental setup consists of a heated pressure vessel capable of confining pressures up to 10 megapascals and temperatures up to 300°C. Roberts takes well-characterized water- and oil-saturated samples and forces carbon dioxide into them, driving oil out in the process. He records the sample's changing electrical properties as the oil is pushed out. Next, he lowers the pressure so that the liquid carbon dioxide changes to the gas phase, and he monitors the electrical changes.

A second type of experiment involves injecting gaseous carbon dioxide and monitoring the electrical properties. All of the experiments are repeated at the different transmitting frequencies that are used in the field.

Roberts notes that samples undergoing carbon dioxide invasion may change geochemically. The nature of the geochemical change depends on such factors as rock chemistry and mineralogy, temperature, pressure, and the chemistry of the fluids inside the rock pores. These changes can affect measured electrical properties. The laboratory data thus help to interpret the EM field data more accurately by improving the resolution between carbon dioxide and oil, which have similar electrical conductivities. "This kind of laboratory work is critical to getting the most information out of the field measurements," says Roberts.

Kirkendall notes that Lost Hills contained an estimated 9 billion barrels of oil. However, after decades of oil production, only 9 percent of the oil has been recovered, because Lost Hills oil is typical California crude—thick and heavy and therefore difficult to pump out of the ground. As a result, 55 percent of the oil currently produced in California comes from EOR methods. At Lost Hills, these methods include hydrofracturing, or breaking up rock layers to create additional pathways for oil to travel, and longer-term waterfloods and steamfloods to sweep trapped oil to the producing wells.

While carbon dioxide injection for EOR provides higher yields than other recovery methods, it is much more expensive than waterflooding. "Water



Two-dimensional images of carbon dioxide flooding in the plane between the two observation wells—one for transmitting, the other for receiving. Image (a) was generated before injection of carbon dioxide and after waterflooding, and image (b) was generated after 3 months of injection. The circles on the left side of each image represent the wells containing the receiver antenna, and the circles on the right side of the images represent the wells containing the transmitting antenna. (c) The difference image is the preinjection image subtracted from the during-injection image and shows areas of change quite clearly. A positive percent difference suggests carbon dioxide is entering the area at the top left. Blue represents water in place, and yellow and red represent the moving oil and carbon dioxide, respectively. Laboratory work is helping to suggest which area is oil and which is carbon dioxide.

flooding is cheap because it can usually be done with brackish water that's available on site," says Kirkendall. As a result, carbon dioxide flooding, if adopted by the industry, would be done only after waterflooding or steamflooding and would be followed by additional waterfloods or steamfloods.

Carbon dioxide flooding is being explored as an option for extending oil production in other states including Kansas and Alaska. Experts estimate that between 2006 and 2010, oil recovered from increasingly depleted Alaskan fields will be too thick to flow in the Alaska pipeline. Injecting water or steam underground would melt the permafrost and collapse wells, so using carbon dioxide might be the best solution.

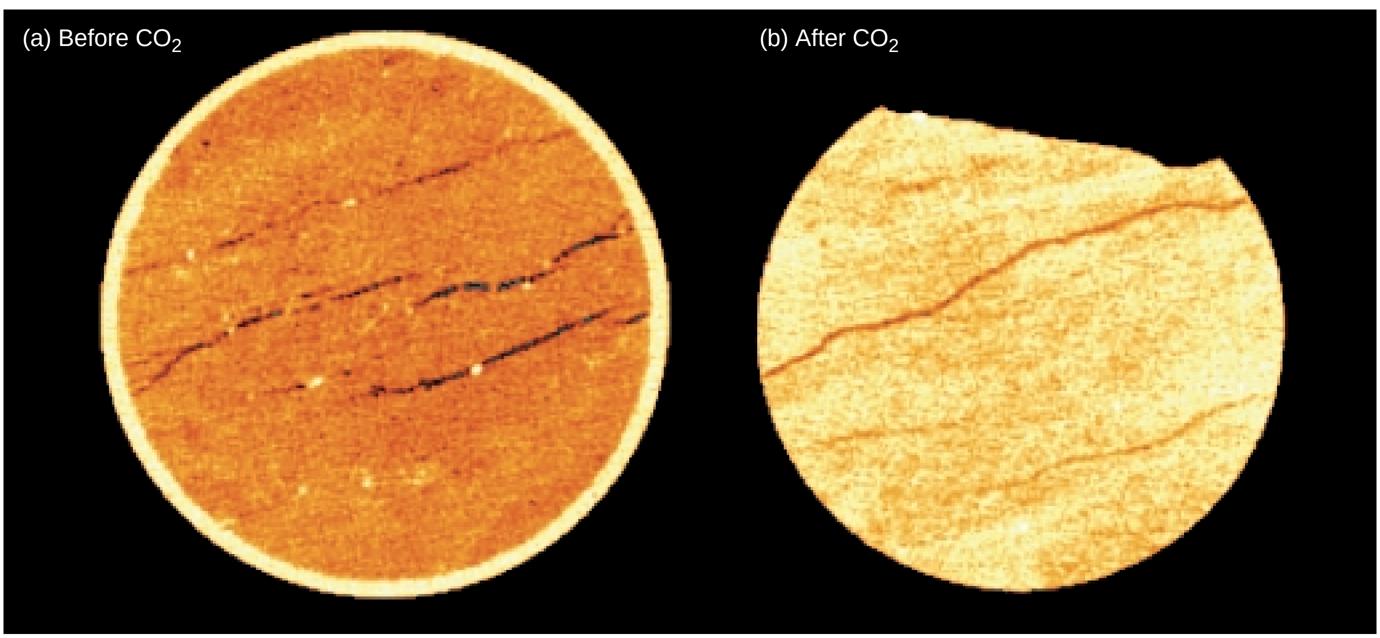
Bringing in trucks carrying liquid carbon dioxide accounts for most of the expense associated with carbon dioxide flooding. But, Kirkendall maintains, "If a pipeline furnished carbon dioxide gas to an EOR site, costs would be dramatically reduced. The idea of building carbon dioxide pipelines has intrigued energy and environmental scientists because power plants and factories produce large amounts of the gas. If the carbon dioxide were to be captured at the smokestack, it could be transported by pipeline to an oil production field for enhanced production."

Kirkendall notes that several new natural-gas-fired power plants were recently approved for California's San Joaquin Valley, close to Lost Hills. The carbon dioxide output of the power plants could be transported to the site by pipeline and injected into the subsurface to assist in EOR, all at a small fraction of the price for trucking in liquefied carbon dioxide. Crosswell EM imaging could then be used to map the carbon dioxide during initial injection. For the highest cost savings, permanent underground electromagnetic transmitters and sensors would be used for long-term monitoring.

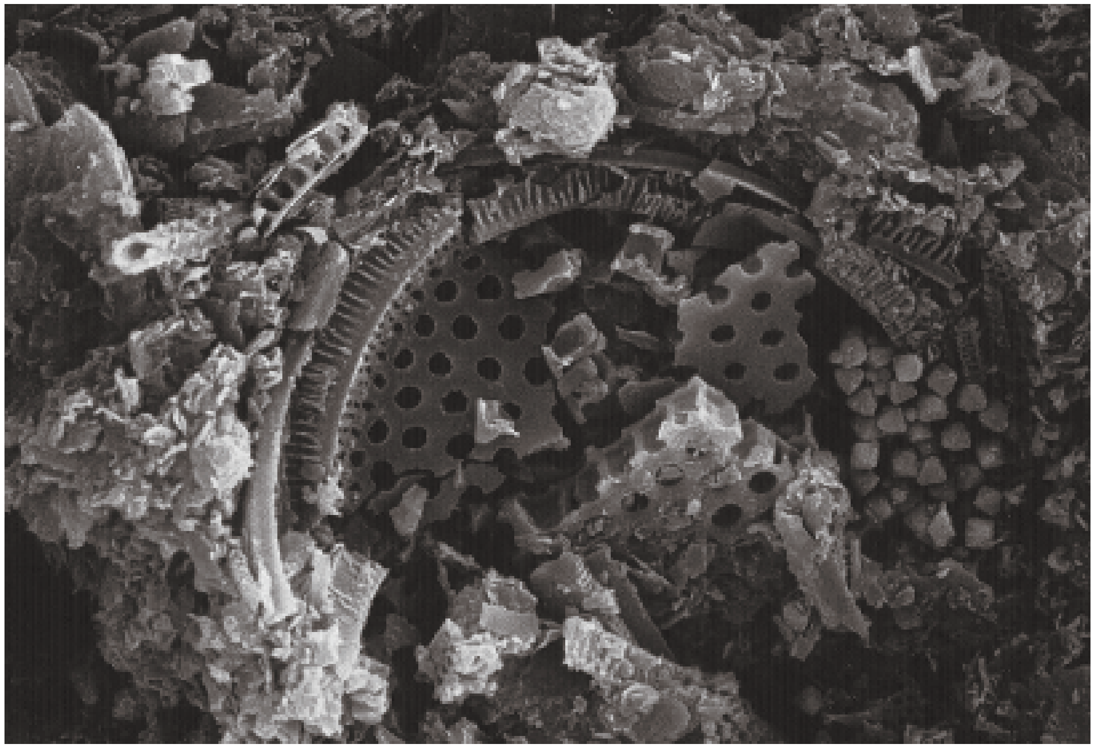
Storing CO_2 for the Environment

Apart from enhanced oil recovery, injecting carbon dioxide underground for long-term storage could become an important way to remove excess amounts from the atmosphere. Carbon dioxide is one of several greenhouse gases that have been linked to rising global temperatures. Significant amounts of carbon dioxide could be removed at the smokestack and then sequestered underground in oil fields and elsewhere instead of released to the atmosphere.

The federal government is considering carbon sequestration as part of its strategy for addressing climate change concerns. "Carbon sequestration is an important option to study because it offers a way to address the global



X-ray images of 5-centimeter-diameter core samples taken from the Lost Hills oil field show the effectiveness of carbon dioxide (CO_2) to sweep oil. (a) A core sample before oil and then carbon dioxide are injected into the sample; (b) the sample after carbon dioxide injection, showing very little oil remaining.



A Chevron scanning electron micrograph reveals what makes extracting oil from the Lost Hills field a challenge: highly porous, low-permeability geologic strata filled with the silica skeletons of microscopic sea creatures, or diatoms (center), and crystals of the mineral pyrite (cubes at center right). (Courtesy of Mike Morea, Chevron USA.)

warming issue without having to make radical overhaul of our existing energy systems," Energy Secretary Spencer Abraham said in July 2001. The Department of Energy's Office of Fossil Energy, which oversees sequestration research, has set a goal of developing carbon dioxide sequestration options that cost $10 or less per ton of carbon, equivalent to adding only 0.2 cents per kilowatt-hour to the average cost of electricity.

As with using carbon dioxide for EOR, sequestering carbon dioxide to help mitigate global warming would require some way to determine its location over time. "Crosswell EM imaging could ensure sequestered carbon dioxide is not leaking back into the atmosphere," says Kirkendall.

The team will continue to monitor the carbon dioxide flood site for another 12 months. Part of that effort will be continuing the laboratory experiments on core samples supplied by Chevron and focusing on ways to more clearly distinguish between carbon dioxide and oil.

Kirkendall presented the initial results from Lost Hills at the DOE's National Energy Technology Laboratory's first annual carbon sequestration conference in Washington, D.C., in May 2001. The response from scientists, representing both research centers and oil companies, was highly enthusiastic.

Extending the Applications

"The techniques we've developed for EOR and carbon sequestration can be extended to several other applications," Kirkendall says. For example, in August, the team visited DOE's complex at Hanford, Washington, the nation's largest environmental cleanup site. The Livermore researchers are studying the use of the technology for tracking the radioactive wastes that are stored in Hanford's underground tanks, the legacy of decades of plutonium production.

The team is also working with Schlumberger and the California Energy Commission to use single-well EM imaging to help guide the location of new geothermal wells. In August, Roberts made a presentation on the geothermal work to the Geothermal Resources Council, a professional organization. Kirkendall says the technology could also be applicable to natural gas reservoir monitoring.

One major challenge is modifying the imaging process so that it works better with wells encased in steel.

Often, sites have one fiberglass well for monitoring, and the remainder are cased in carbon steel, a material that significantly weakens EM signals. As a result, the potential commercial application of crosswell EM imaging depends on how well the procedures and modeling codes handle electromagnetic transmission through steel casing. In the studies at Lost Hills, both the transmitter and receiver wells are fiberglass.

Another task includes developing permanent, inexpensive sensors for long-term monitoring at much lower costs. Permanent underground sensors are a particularly attractive option for long-term carbon dioxide sequestration. Based on the results so far, the imaging team is confident crosswell EM imaging has a strong future in the nation's energy and environmental future.

—Arnie Heller

Key Words: carbon sequestration, crosswell electromagnetic (EM) imaging, enhanced oil recovery (EOR), oil production.

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About the Scientists

BARRY KIRKENDALL received a B.Sc. in physics from the University of California at San Diego in 1992 and an M.Sc. in geophysics from the Colorado School of Mines in 1998. Before joining the Laboratory, he was a staff research assistant at the Scripps Institute of Oceanography in La Jolla, California, with a focus on ocean-bottom seismology, and an electrical engineer at Caterpillar Research Facility in Illinois, where he was involved in the development of a ground-penetrating radar system for rapid near-field imaging. He came to Livermore in 1998 as a physicist responsible for managing a project to develop cross- and single-well electromagnetic subsurface imaging and associated data-acquisition systems. Current projects include near-surface high-frequency three-dimensional imaging, multiple frequency imaging at oil and gas sites, and near-wellbore imaging of fracture systems at geothermal sites. The emphasis of this research is on using electromagnetic induction imaging coupled with petrophysical research to monitor enhanced oil recovery through carbon dioxide injection and sequestration. Kirkendall is the principal investigator responsible for field studies for this enhanced oil recovery research at Livermore.

JEFF ROBERTS came to the Laboratory in 1992 as a geophysicist. He received his B.S. in applied science from the University of Texas at San Antonio in 1985 and his Ph.D. in geology from Arizona State University in 1992. His primary research interests include the electrical properties of minerals and rocks, the physics of flow and transport, the physical properties of porous media, and the microscale imaging of materials to reveal flow and transport. He also researches solid-earth geophysics, particularly the experimental determination of the physical properties of rocks and minerals, with the goal of more fully understanding the composition and dynamics of Earth's interior. He is the coauthor of numerous journal articles on these topics. He is currently the principal investigator responsible for laboratory experiments on Livermore's project using electromagnetic induction imaging to monitor enhanced oil recovery through carbon dioxide injection and sequestration.